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PROCESSING FOR CAST COMPONENTS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. provisional patent applications Serial Nos. 60/577,055, filed June 4, 2004; 60/497,601, filed August 25, 2003; and 60/495,079, filed August 14, 2003, all of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to improved processing methods for cast components, including cast compressor wheels and cast turbine wheels, especially for turbochargers, industrial compressors, and gas turbines, and also for any application in which improved fatigue strength and/or fracture toughness is desirable.

BACKGROUND OF THE INVENTION

The mechanical performance and cost of many objects are directly related to the methods employed in the design of the object and also to the materials chosen for fabrication of the object. Fabricating the same object from different materials can result in widely different performance and cost. As one example, in the field of centrifugal compressors for turbochargers, there are many applications in which the compressor wheel is cast from aluminum. However, commonly processed cast aluminum compressor wheels have certain limitations in terms of their longevity. As long as the operation of the turbocharger, such as in terms of rotating speed, maximum temperature, and temperature cycling, is within the limitations of the cast aluminum material, the user will experience satisfactory performance. However, some types of usage, such as a turbocharged engine for internal combustion engines used in high performance applications such as on-highway trucks and off highway construction and agricultural applications and high performance automobile engines, may

impose operating conditions so severe that cast aluminum will fracture and fail as a result of low cycle fatigue and/or high cycle fatigue. In some of these more severe applications, it is known to forgo cast aluminum as the material of choice, and instead use titanium. The higher strength properties of titanium will restore adequate life to the compressor wheel, but only at a significant cost in light of the expense of the raw material, difficulties in machining, and other concerns. Therefore, some turbocharged engines use titanium compressor wheels which greatly increases the initial cost of the turbocharger. In many of these applications, the use of titanium is "overkill", the titanium providing material properties far in excess of even some extreme environments.

What is needed is a manufacturing method which provides cast aluminum parts with material properties better than those obtained with commonly known cast aluminum, but without the expense of titanium. The present inventions do this in novel and unobvious ways.

SUMMARY OF THE INVENTION

One embodiment of the present invention relates to methods for casting a component with subsequent cryogenic processing. The cryogenic processing may be followed with other types of heat treatment, including precipitation hardening as one example.

Another embodiment of the present invention pertains to casting a rotating component from aluminum. The rotating component is cooled to a temperature less than about –150 degrees C. After the component is warmed to about room temperature, the component is machined.

In another embodiment of the present invention, there is a composition for material which comprises mainly aluminum. There is sufficient silicon added to the aluminum to improve castability. The composition includes from about 0.1 percent to about 1 percent by weight scandium, or from about 0.1 percent to about 1 percent lithium, or combinations of scandium and lithium within those same ranges.

These and other aspects of various embodiments of the present invention will be apparent from the description of the preferred embodiment, claims, and drawings to follow.

DESCRIPTION OF THE DRAWINGS

FIG. 1A is an end elevational view of a turbocharger compressor wheel according to one embodiment of the present invention.

FIG. 1B is a side elevational view of the compressor wheel of FIG. 1A.

FIG. 1C is a cross sectional view of the compressor wheel of FIG. 1A.

FIG. 2 is a flow chart showing the order of various processes according to one embodiment of the present invention.

FIG. 3 is a Weibull plot of percent failure verses cycles to failure for a cast aluminum compound processed with prior art methods.

FIG. 4 is a Weibull plot of percent failure verses cycles to failure for a cast aluminum compound processed according to one embodiment of the present invention.

FIG.5 is a Weibull plot of percent failure verses cycles to failure for a cast aluminum compound processed according to another embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the embodiment illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, such alterations and further modifications in the illustrated device, and such further applications of the principles of the invention as illustrated therein being contemplated as would normally occur to one skilled in the art to which the invention relates.

Various embodiments of the present invention relate to improved materials or improved material processing, or the combination of both, that are applicable to cast aluminum. Yet other embodiments of the present invention relate to improvements in material processing for high strength, high temperature alloys such as Inconel (IN) 713C, IN713LC, IN-738, and IN-100 or GMR235, or related materials that are conventionally used for the turbine [hot side] of a turbocharger. It is thought that by cryogenically treating these components, and other marginally designed turbocharger components, that the overall reliability of the components and the turbocharger will be substantially improved. It has been found that cryogenic processing of a castable aluminum material, including those aluminum compositions with significant additions of silicon, provide greatly increased fatigue strength compared to non-cryogenically cast aluminum alloys. The increases in fatigue strength were unexpected because of the many differences between ferrous v. nickel vs. aluminum alloys, or wrought vs. cast materials, or non-silicon bearing materials vs. silicon-bearing castable materials. Based on the results of coupon testing as documented herein, significant improvements in material properties are obtained with cryogenic processing, and cryogenically processed cast aluminum can be considered a replacement for titanium in some

applications. As one example, application of cryogenically processed cast aluminum as discussed herein can replace wrought or forged titanium in some turbocharger compressor wheels, thus avoiding the 10X to 15X cost penalty incurred by the use of titanium.

Some embodiments of the present invention pertain to improved compositions of castable aluminum. It is believed that adding up to about 1 percent lithium and/or up to 1 percent scandium improves the material properties of castable aluminum alloys which also include silicon-magnesium or silicon-magnesium-copper. For instance, the addition of lithium is thought to improve the fracture toughness of the castable aluminum.

Some embodiments of the present invention relate to material compositions and processing methods which improve the material properties of cast aluminum, including the fatigue strength and / or the fracture toughness of cast aluminum. Such material and processes can be applicable to a variety of static components, including cast aluminum housings such as for automatic transmissions and transfer cases, compressors, valve assemblies, and the like. These material and processes are also applicable to a variety of dynamic components, including rotating components, such as pinion gear carriers, automatic transmission clutch housings, air conditioner rotors, valves, piston pumps, centrifugal pumps, seals and seal carriers, and rotary and linear actuators.

According to one embodiment of the present invention, there is an improved composition for cast aluminum. In one embodiment, the cast aluminum includes percentages of silicon, magnesium, and other elements similar to that found in commercially available C355 aluminum, but also including up to about 1 percent lithium. In another embodiment of the present invention, the cast aluminum includes percentages of silicon, magnesium, and other elements similar to that found in commercially available C355 aluminum, but also including up to about 1 percent scandium. In another embodiment, the cast aluminum includes percentages of silicon, magnesium, copper and other elements similar to that found

in commercially available 354 or A354 aluminum, but also including up to about 1 percent lithium. In another embodiment of the present invention, the cast aluminum includes percentages of silicon, magnesium, copper and other elements similar to that found in commercially available 354 or A354 aluminum, but also including up to about 1 percent scandium. It is believed that the cryogenic processing described herein may also improve the fatigue strengths of castable, commercially available aluminum alloys such as A357, D357, A201, B201, and 203.

In another embodiment of the present invention, there are various methods for processing cast aluminum. These methods apply to any type of cast aluminum, but in particular cast aluminum including amounts of silicon, magnesium, and other elements similar to C355, and also for cast aluminum including silicon, magnesium, copper, and other elements similar to the composition known as 354 or A354. Further, the processing methods are applicable to the novel compositions of cast aluminum including lithium, scandium, and combinations of lithium and scandium, as described herein.

In one embodiment of the present invention, these methods include preparing a casting from the aluminum material, cryogenically processing the cast object, and then machining the object. In some embodiments the cryogenic processing occurs during exposure to temperatures reached by use of liquid nitrogen (LN2) at about ambient pressure. Cast aluminum objects processed according to this method have been shown to have higher, usable high cycle fatigue strength. In yet other embodiments of the present invention, the processing methods include one or more pre-cryogenic processing steps. In yet other embodiments of the present invention, there are one or more post-cryogenic processing steps. In yet further embodiments of the present invention, there are various processing steps after machining, including cryogenic processing. The term "steps" as used in the Description of

the Preferred Embodiment is used generically and not with regards to "steps" as used in 35 U.S.C. § 112.

In still further embodiments of the present invention, there are materials and processes used to cast and process a compressor wheel for a turbocharger. In some embodiments, the compressor wheel is cast from any of the novel aluminum compounds described herein, such as those including lithium, scandium, or lithium and scandium. In other embodiments of the present invention, the turbocharger wheel is cast from aluminum and is processed with any of the cryogenic processing methods described herein. In yet other embodiments of the present invention, a turbocharger wheel is cast from any of the novel aluminum compounds described herein, and further processed according to any one of the cryogenic methods described herein.

In yet further embodiments of the present invention, there are materials and processes used for casting and processing a turbine wheel for a turbocharger. In some embodiments, the turbine wheel is cast from a material such as Inconel 713C or GMR235, or other materials used for fabrication of cast or non-cast turbine wheels for turbochargers. In other embodiments of the present invention, the turbocharger turbine wheel is cast from a material such as IN713C or GMR235 and is further processed with any of the cryogenic processing methods described herein. Although reference hereafter will be made to processing of compressor wheels, it is understood that the present invention also applies to processing of turbine wheels, as well as processing of any material.

FIGS. 1A, 1B, and 1C show various views of a compressor wheel 30 according to one embodiment of the present invention. Compressor wheel 30 includes a plurality of blades 32 which are cast integrally about a hub 34 and a back plate 36. In some embodiments of the present invention, compressor wheel 30 compresses ambient air for use in industrial applications including gas pipelines. In yet other embodiments of the present invention,

compressor wheel 30 provides compressed air to an internal combustion engine, the compressor wheel being driven by a turbine, and being part of a turbocharger assembly (not shown). In yet other embodiments of the present invention, compressor wheel 30 provides compressed air to a second compressor and and/or combustor for a gas turbine engine, including both industrial gas turbines and aircraft engines.

In another embodiment of the present invention, an object is cast from an aluminum alloy which includes up to about 1 percent by weight of lithium and more than about 0.1 percent by weight by lithium which can improve strength & toughness. In some embodiments, the addition of lithium improves the fracture toughness of the material. In other embodiments of the present invention, the object is cast from aluminum alloy which includes up to about 1 percent by weight of scandium and more than about 0.1 percent by weight of scandium. In other embodiments of the present invention, an object is cast from an aluminum alloy containing up to about 1 percent by weight of lithium and up to about 1 percent by weight of scandium and more than about 0.1 percent by weight of lithium and more than about 0.1 percent by weight of scandium.

As one example, the base cast aluminum alloy to which either lithium, scandium, or lithium and scandium, are added contains about 5 percent by weight silicon, about 1.2 percent by weight copper, and about 0.5 percent by weight magnesium and in some cases other elements. This base aluminum may be known by the trade name C355. In yet other embodiments of the present invention, the material includes about 9 percent by weight silicon, about 1.8 percent by weight copper, about 0.5 percent by weight magnesium, and other elements. This base material may be known by the trade name 354 or A354. In one embodiment of the present invention the cryogenically processed castable aluminum includes more than about four percent by weight silicon and less than about ten percent by weight silicon. In yet other applications, the cryogenically processed castable aluminum includes

from about four and one-half percent by weight silicon to less than about nine percent by weight silicon. In yet other embodiments the cryogenically processed castable aluminum includes from about four and one-half percent by weight silicon to less than about seven and one-half percent by weight silicon.

The novel alloys described herein, especially when heat-treated and/or hot isostatic pressing (HIPped), exhibit improved yield strength and tensile strength associated with higher elongation and improved fatigue resistance.

Although the addition of lithium, scandium, or lithium and scandium into cast aluminum compounds similar to 354 or A354 and C355 has been described, the present invention is not so limited. The present invention contemplates the addition of lithium, scandium or lithium and scandium to any aluminum alloy used in casting processes.

Referring to FIG. 2, there is a processing method 100 for producing cast aluminum objects with improved physical properties. In various embodiments of the present invention, the steps of methods 100 are applicable to the novel cast aluminum alloys described herein, and further are applicable to processing of wheels for centrifugal compressors.

Method 100 includes a step 110 in which a castable aluminum alloy is provided. The aluminum alloy may be of the type known commercially as C355, 354 or A354, or their equivalents. Further, the castable aluminum alloy can include any of the novel compositions described herein which include lithium, scandium, or lithium and scandium. In addition, various embodiments of the present invention are applicable to any cast aluminum alloy.

Step 120 includes preparing a casting from the aluminum material. The present invention contemplates any method for casting, including casting from sand, lost wax, ceramic and/or plaster based materials and from permanent dies. The object simulated by the casting can be of any type, the present invention not being limited to any maximum part thickness or minimum part thickness. In one embodiment the cast aluminum is poured under

a vacuum assist with dross-free metal. In some embodiments of the present invention the castable aluminum material is conventional, whereas in other embodiments the castable aluminum is alloyed with lithium, scandium, or lithium and scandium.

In step 130, some embodiments of the present invention include pre-cyrogenic processing, such as hot isostatic pressing (HIP). In one embodiment the HIPping process includes process parameters of 2 to 4 hours at a pressure of about 105MPa at temperatures from about 480°C to about 530°C. However, the present invention is not limited to these parameters, and may be HIPped by equivalent methods.

In other embodiments of the present invention, step 130 further includes solution heat treating the casting for 10 to 12 hours at about 520°C to about 530°C. Following solution heat treating, step 130 may further include quenching the part in water at about 60°C to about 80°C. Although a step 130 of precryogenic processing has been described which includes HIPping, solution heat treating, and quenching, step 120 can also comprise only HIPping, or only solution heat treating followed by a quench.

The object is cryogenically processed as indicated by step 150 which may occur after precryogenic processing step 130, or alternatively occur after the casting has been prepared at step 120. In one embodiment, the cryogenic process includes process parameters of 8 to 48 hours at about -200°C to about -180°C. The cryogenic temperatures can be obtained by the use of liquid nitrogen at approximately ambient pressure. Further, the object is cooled to cryogenic temperatures, and subsequently heated to ambient temperature, at the rate of about 50°C per hour. However, the present invention is not limited to these process parameters. In particular, small cast aluminum wheels can be processed with higher cooling and heating rates and for less time, based on the high thermal conductivity of aluminum and the high ratio of surface area to weight as exhibited in components such as wheels for centrifugal compressors.

Following a first cryogenic processing at step 150, some embodiments of the present invention include a post-cryogenic processing step 160. For example, this post-cryogenic processing can include annealing the cast object to relieve internal stresses. This stress relief anneal can include process parameters of 24 to 30 hours at about 130°C to 140°C. In other embodiments of the present invention, post-cryogenic processing step 160 includes a heat treat for precipitation hardening of the cast object. This heat treat can include process parameters of 8 to 12 hours at about 150°C to about 160°C.

Although it has been shown and described as post-cryogenic processing that includes annealing and precipitation hardening, some embodiments of the present invention include only one of these processing substeps. Yet other embodiments of the present invention do not include any heat treating of the object after cryogenic processing step 150 and before machining step 180.

In some embodiments of the present invention, there is a second cryogenic processing step 170 following step 160. This second cryogenic processing is performed with process parameters as previously described. However, in those embodiments of the present invention in which there is no post-cryogenic processing step 160, there is also no second cryogenic processing step 170.

Following post-cryogenic processing step 160 and/or cryogenic processing steps 150 or 170, the object is machined at step 180. The present invention contemplates any kind of machining methods, including machining methods that remove material such as, for example, grinding, boring, cutting, turning, and honing. Following machining, some embodiments of the present invention include post-machining processing as indicated by step 190. Step 190 can include an annealing for stress relief, such as with the annealing process parameters described previously. It is thought that cryogenic processing improves the characteristics of a component, including the component's fatigue strength, by reducing residual stresses. For

those applications in which the machining of a component induces residual stresses, step 190 can include an additional processing at cryogenic temperatures. However, some embodiments of the present invention do not include any further processing steps after machining step 180. Yet other embodiments of the present invention include either annealing or cryogenically treating, but not both steps.

An improvement in material properties after cryogenic treating of a cast aluminum alloy according to one embodiment of the present invention has been demonstrated with test coupons in a high-cycle fatigue test. Fatigue test bars of a conventional cast aluminum alloy were prepared and tested in accordance with the R.R. Moore test procedure.

FIGS. 3, 4, and 5 depict the improvement demonstrated by various embodiments of the present invention. Test coupons were cast from 354 Aluminum which was heat treated in accordance with T61 (standard designations of the Aluminum Association). FIG. 3 shows a Weibull plot for coupons of a conventional aluminum alloy that were processed with a solution heat treat followed by aging. The data points are represented by dots within circles. A best-fit straight line 202 is shown on FIG. 3.

FIGS. 4 and 5 depict the effect of cryogenic processing of similar coupons in the same test procedure. The coupons were cryogenically treated for about 24 hours in a temperature range from about –190 degrees Centigrade to about –210 degrees Centigrade. FIG. 4 was prepared for coupons of the same aluminum alloy that were solution treated, aged, and then cryogenically treated. Best-fit straight line 204 is shown superimposed on the data set from this first type of cryogenic processing.

FIG. 5 shows a best-fit straight line 206 superimposed on a data set from a second type of cryogenic processing. The coupons used for the data shown in FIG. 5 were prepared from the same aluminum alloy and were then solution treated, followed by cryogenic processing, followed by aging. Note that the best-fit straight line 206 is shifted to the right

and downward relative to line 204, and that line 204 is shifted to the right and then downward relative to the line 202. These data shifts indicate that the processing of the coupons in FIG. 4 provides improved high cycle fatigue strength from the non-cryogenically processed coupons represented in FIG. 3. Further, the modified cryogenic treatment of the coupons represented in FIG. 5 are likewise improved relative to the cryogenically treated coupons represented in FIG. 4. Further, note that the data points of FIG. 5 appear to have less data scatter than the data points of FIG. 4 or FIG. 3, indicating that not only is the high cycle fatigue improved, but that the high cycle fatigue properties are statistically more uniform. The coupons in these tests were run in a tension-axial fatigue stress (3000 to 30,000 psi) with a stress ratio of 0.1. These coupons have demonstrated an improvement in the fatigue life of the cast aluminum of about 2.5 times the non-cryogenically processed fatigue limit, with about 90 percent confidence.

In one embodiment of the present invention, there is a method for processing an aluminum casting. The method comprises providing an aluminum casting, cryogenically treating the aluminum casting, and machining the aluminum casting after the cryogenic treatment.

In another embodiment of the present invention, the method further comprises HIPping the casting before the cryogenic treatment. In yet another embodiment of the present invention, the method further comprises solution heat treating the casting before the cryogenic treatment. In yet another embodiment, the casting is aged after this solution heat-treating and before the cryogenic processing. In yet embodiment of the present invention, the method comprises aging the cast object after the cryogenic treatment and before the machining. In yet another embodiment, there is a second cryogenic processing after the aging. In a further embodiment, there is a third cryogenic treatment after the machining.

In yet another embodiment of the present invention, there is a castable aluminum material including silicon and magnesium. In another embodiment, the material further includes up to about 1 percent lithium. In another embodiment, the aluminum material includes up to about 1 percent scandium. In yet another embodiment, the aluminum material includes up to about 1 percent lithium and up to about 1 percent scandium. In a further embodiment of the present invention, the aluminum material also includes copper.

While the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only the preferred embodiment has been shown and described and that all changes and modifications that come within the spirit of the invention are desired to be protected.